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Title: Extending participatory research through simulation modeling: benefits, risks and tradeoffs of legume diversification in smallholder maize systems

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Abstract

Crop simulation models have often been proposed as means to explore cropping system design questions in variable climates yet there are few examples that examine the decadal response of soils and crops within a smallholder farm context. Integrated soil fertility management strategies based on legume diversification of cereals in sub-Saharan Africa have shown promise for improving smallholder yields. Participatory research methods have identified pigeonpea (*Cajanus cajan*) as a promising, multipurpose legume for improving fertility and productivity in maize (*Zea mays*) systems. However, including a long-duration legume like pigeonpea may create a trade-off between improved soil fertility and increased water uptake, potentially imposing water stress on the maize crop depending on soil type and rainfall regime. This effect is difficult to quantify using short-term field trials, particularly in the context of participatory research where variability is high.

Here we used the Agricultural Production Systems Simulator (APSIM), parameterized with data from on-farm trials, to evaluate maize-pigeonpea rotation and intercrop systems. Model experiments at two sites, Zombwe and Kasungu, show that at low fertilization levels (24 kgN/ha applied to maize) both intercrop and rotation systems outperform continuous maize. While soil water and nitrogen trade-offs exist, particularly at the driest site, the overall effect was positive. Maize yield following pigeonpea was very rarely lower than maize yield following maize, 3 to 7% of the time, depending on the soil type. Increased time from establishment enhanced yield benefits associated with legume diversification at both sites, and benefits appear to be greater in sandy, low fertility soils than for fine-textured, higher fertility soils. The risk of crop failure was less than 10% in all cases for the rotation system. While the risk in the intercrop system was 10-30% in the initial establishment phase, it dropped below 10% after 3 years. Our results suggest that maize-pigeonpea systems are viable, low-risk options for improving crop production and soil fertility that can be targeted to low fertility soils to obtain the maximum benefit.

Keywords: APSIM; maize; legume; crop model; smallholder farmers; pigeonpea

1. Introduction

In previous decades, agricultural research has led to new strategies that show potential to increase yields for smallholder farmers in sub-Saharan Africa. Despite this, yields on the continent have stagnated (Sanchez, 2010). Lack of adoption may be due to promotion of inappropriate technologies, or lack of capacity in extension systems to disseminate new information effectively. Participatory research methods have been developed to mitigate some of these issues, and have been used in areas that include plant breeding, testing of new varieties, as well as soil fertility and natural resource management. Methods such as mother-baby trials

(Snapp et al., 2002) are used to create opportunities for co-learning, where researchers and farmers collaborate to achieve research objectives. As a result of engaged research, integrated soil fertility management strategies have been developed that incorporate fertilizer and organic technologies to maximize nutrient use efficiency and crop productivity (Vanlauwe et al., 2010).

Scaling up of field research on soil fertility management is challenging. Research at field stations often does not account for variability in soils and the environment found under smallholder conditions. Participatory research better represents the range of smallholder conditions, but variability can be extremely high. As such, new strategies are needed to move beyond the local and short-term scales at which new technologies are frequently tested. There has been a limited number of studies of ecological systems over decadal time scales (Hastings et al., 2007). This limitation poses a significant challenge for agricultural systems, as many important processes, such as changes in soil C and N, require multiple years to detect. In addition, variability in space and time combine to create particular challenges for testing long-term technology performance in a complex environment (citation?).

Models are an important research tool, as they provide a low-cost way to explore agricultural system performance along with environmental interactions over long time scales. It is surprising, then, that there are relatively few examples of model application over multiple years to address year-to-year dynamics of agroecological systems within a smallholder farm environment. Crop simulation studies generally involve regular resets, as illustrated by Dixit et al. (2011) and Robertson et al. (2005), to reduce carry-over errors and allow for unbiased year to year comparisons. Other studies look at aggregate effects of changes in farming systems or management practices over a period of years (e.g., Tittonell et al., 2009, Rufino et al., 2010). These two approaches miss the opportunity to explore how plant and soil interactions evolve

from year to year, and these interactions are at the foundation of integrated soil fertility management and sustainable intensification.

Diversification of maize cropping with the long-duration legume pigeonpea (*Cajanus cajan*) has been identified as a promising integrated soil fertility management system in southern Africa (Snapp et al. 2010). Farmers in Malawi have adopted systems including pigeonpea in rotation with maize and in maize-pigeonpea intercrops, as well as rating these systems highly in farm interviews and surveys (Bezner Kerr et al., 2007; Mhango et al., 2012). Benefits observed in pigeonpea systems include food during off-season periods, high value protein-enriched products, and improved maize yields in the following year. These systems have also been shown to provide good returns to investments in labor and fertilizer in a four-year on-farm trial in central Malawi (Kamanga et al., 2009). However, including a long-duration and deep-rooted legume like pigeonpea or an agroforestry tree crop in a rotation has been shown to increase water use and reduce water available to the main food crop in the following year (Wortmann et al. 2000), potentially reducing yield. In addition, drought stress can decrease the capability of legumes to fix nitrogen, thereby reducing soil fertility benefits (Dakora and Keya 1997). Due to these potential trade-offs, identifying conditions under which long-duration legumes provide the greatest benefits is a necessary first step in scaling up this promising technology. Soils in Malawi, as elsewhere in Africa (e.g., Zingore et al., 2010, Tittonell et al., 2005), are spatially heterogeneous, even over short distances (Snapp, 1998). In addition, Malawi exhibits high spatial and temporal variability in rainfall (Ngongondo et al., 2011). This inherent environmental variability, particularly when combined with the variability associated with on-farm research, means extrapolating results can be nearly impossible, since conditions change markedly from year to year and site to site. In addition, few studies exist that measure the long-term effects

associated with shifting from maize monoculture to legume-diversified systems, despite evidence that such effects occur (Liebig et al., 2002).

Linking participatory research with crop simulation modeling could markedly enhance our understanding of the processes underlying interactions among soil type, climate, and crop yields (Whitbread et al., 2010). Simulation modeling, in an agricultural development context, has been used successfully in conjunction with field experimentation to extrapolate findings and assess technology performance (e.g., Gowing et al. 2003; Chikowo et al. 2008). Models have also been used to match integrated soil fertility management practices to appropriate agro-ecological niches defined by climate and soil type, and to tailor interventions to meet the needs of different types of farmers (Giller et al., 2010). In addition, crop models can be used as a tool for engagement with farmers, or as a learning tool for policymakers. A thorough review of crop simulation model uses can be found in Whitbread et al. (2010). Despite the clear value for inference over time and space, use of crop simulations has rarely been linked directly with participatory on-farm research (for one example, see Dimes et al., 2003).

The Agricultural Production Systems Simulator (APSIM) is a modular cropping systems model that was developed for simulation of a wide variety of cropping systems. Modules for diverse crops including maize, pigeonpea, soybean, and groundnut have been developed, as well as modules for simulating various soil processes including water and soil carbon dynamics, along with phosphorous and nitrogen budgets (Keating et al. 2003). APSIM is capable of simulating intercrop systems including maize-legume systems (Carberry et al., 1996), and has been used extensively in Eastern and Southern Africa under both research station and smallholder conditions (citation?). APSIM has also been found to perform well when used to simulate responses to nitrogen fertilizer in Zimbabwe (Shamudzarira and Robertson, 2002), and rotational

effects with green manure legumes in Malawi (Robertson et al., 2005). In addition, APSIM has been used to conduct risk analyses, using longitudinal climate records to test management strategies. For instance, Dixit et al. (2010) used APSIM to evaluate the range of maize response to fertilizer and economic returns based on long-term climate variability for a high-productivity site in Kenya. Shamudzarira and Robertson (2002) explored the combined effects of N and water in a semi-arid environment, and evaluated risk for different fertilization scenarios. These studies investigated short-term effects over one or two year periods, but models such as APSIM can also be used to explore potential long-term cumulative impacts of changes in management (Carberry et al., 2002;). By using simulation models run over long continuous time series, it is possible to explore the longer-term consequences associated with changes in management practices (Carberry et al., 2002).

While participatory research has identified the potential of maize-pigeonpea systems to increase maize yields under smallholder conditions (Snapp et al., 2010), important questions remain with respect to scaling up in space and time. We used the crop simulation model APSIM to address two objectives. Our first objective was to replicate yields found in participatory trials on smallholder fields, using collected data. We aimed to simulate yields to within one standard deviation of observed yields in field trials, and to match relative yields in maize monoculture and maize-legume systems. Our second objective was to use the model to answer further questions about the cropping systems simulated. Our specific research questions were:

1. What is the impact of legume diversification on maize yield over time, and under what soil and climate conditions are legumes most beneficial?

2. Does the use of pigeonpea increase the risk of crop failure in rain fed maize-based systems? Further, does risk diminish if maize-pigeonpea systems are continued over multiple years?

3. To what extent does increased water use by pigeonpea create trade-offs between soil fertility benefits and increased soil water use in maize-pigeonpea diversified systems? And finally, how do soil and rainfall conditions influence these trade-offs?

2. Materials and Methods

2.1. Field sites

Data for model parameterization were obtained from field trials conducted in Ekwendeni, Mzimba district, in northern Malawi, during the three growing seasons between 2007 and 2011 (Mhango, 2011). Yield and biomass data, as well as soil data including organic carbon content, soil texture, and pH in surface and subsurface layers were collected from 19 farmer-managed field sites in 5 villages. Soil types at the field sites were generally sand to sandy clay with low levels of organic matter, classified as fine kaolinitic, thermic, typic kandiustalfs (Mhango et al., 2012). Rotation and fertility treatments used in modeling consisted of: continuous maize with two nitrogen fertilization levels (24 and 92 kg N ha^{-1}); a pigeonpea-maize rotation with 24 kg N ha^{-1} applied only to maize; and a maize-pigeonpea intercrop, with 24 kgN ha^{-1}. Nitrogen was applied as urea at four weeks after planting (WAP) in the 24 kg N ha^{-1} treatments. In the 92 kg N ha^{-1} treatment urea was applied in a split application with 23 kg N ha^{-1} applied at planting and 69 kg N ha^{-1} applied at four WAP. The maize variety used in field trials was MH-17, and the pigeonpea variety used was ICEAP 00040.

For modeling purposes, soil characterization was required. Soils varied across farms, and we were interested in understanding the effects of this variation, however limited data precluded the use of different model soils for each individual farm. Therefore, we used soil data collected during baseline soil sampling in 2007 (Mhango, 2011) from 20 field sites to define three soil types for modeling: high fertility (soil HF), medium fertility (soil MF), and low fertility (soil LF). Soils were grouped based on soil organic C (OC) and soil texture, then average properties were calculated for each soil type. Soil HF was defined by soils with OC > 0.7% and sandy loam soil texture, with an average of 63% sand and 27% clay. The average OC of soil HF was 0.78%. Soil MF included soils containing OC <0.7% and sandy loam texture, with an average of 63% sand and 27% clay. The average OC of soil MF was 0.58%. Soils classified as soil LF also had OC < 0.7%, but had an average sand content of 79% and an average OC of 0.58%.

In order to quantify inorganic N, soil OC and bulk density throughout the soil profile as needed for modeling, four representative fields were chosen in mid-July 2011 from among the on-farm research sites (Mhango et al., 2012). At each site, two plots were chosen and four samples were taken per plot (6.4 cm diameter soil augur), to a maximum depth of 120 cm. Intervals sampled were 0-15, 15-30, 30-60, 60-90, and 90-120 cm, and each depth interval was composited. Samples were well mixed, air-dried and sieved to pass a 2mm sieve, and analyzed at Michigan State University. Nitrate (NO3)-N was extracted (1 M KCl) from soil collected at the 0-15 and 15-30 cm depths, and measured spectroscopically following the method of Doane and Horwath (2003). Samples for OC analysis were ground to powder (SPEX SamplePrep, Model 8515, Metuchen, NJ) and analyzed using a dry combustion C and N analyzer (Costech ECS 4010, Costech Analytical Technologies, Valencia, CA). Soil bulk density measurements were conducted using 7.6 cm diameter cores from the two faces of each soil pit, dug to a depth of 1.2

m at each site. Four cores were taken at depths of 0-15, 15-30, 30-60, 60-90, and 90-120 cm and averaged by depth.

2.2. Model Setup

The crop simulation model APSIM was used to model all treatments. APSIM requires inputs of daily weather data, including maximum and minimum temperature, precipitation, and solar radiation. For model calibration, daily rainfall data for the years 1945-2011 and long-term average monthly temperature data were available from the Zombwe Extension Planning Area, approximately 5 km from the Zombwe field sites. Zombwe (11.33°S, 33.82°E, altitude 1143 m.a.s.l.) has an average of 783 mm of rain per year which was concentrated between mid-November and early May. The model was also run using the long-term temperature and rainfall record for the years 1927-2010 from Kasungu, Malawi (13.03°S, 22.45°E, altitude 1036 m.a.s.l.), which allowed us to investigate the applicability of this system to a slightly drier site in a different part of Malawi. Kasungu has an average of 739 mm of rain per year which was also concentrated between mid-November and early May. Weatherman, a part of the DSSAT software suite (Pickering et al., 1994), was used to generate daily temperatures and solar radiation, as well as to fill in gaps for the rainfall record at both sites. Missing values in rainfall records were concentrated during dry seasons, so should have limited influence on model results.

The soil modules in APSIM require a number of parameters. Soil total OC, NO_3 and BD were defined from values measured during sampling in 2011 as described above. Soil carbon fractions (biomass and inert C) were defined following Chikowo et al. (2008). The inert fraction was 0.6 in the topmost layer, increasing to 0.99 at 1.2m. The biomass fraction was 0.03 in the topmost layer, decreasing to 0.01 at 1.2 m. Volumetric soil moisture content at permanent wilting

point, field capacity, and saturation were also required, and were derived from texture and bulk density using pedotransfer functions following Saxton and Rawls (2006). This method was selected based on evaluations of a number of common pedotransfer functions by Gijsman et al. (2002), where their analysis found that an earlier version of Saxton and Rawls' method (Saxton et al., 1986) performed the best out of the eight methods they tested. The updated version used here is similar. Texture from 0-30 cm was calculated as the average within each of the three soil groups (i.e., soil LF, MF, and HF) defined from 2007 data (Mhango, 2011). Data for soil texture below 30 cm was not available due to difficulties processing deeper soil samples, therefore following Chikowo et al. (2008) soil texture below this was assumed to be constant. Additionally, field examination of soils did not suggest any major changes in soil texture below 30 cm depth. Soil properties are described in Table 1.

There were two types of model runs used here: a calibration model, and a time-series model. The calibration model was created to ensure APSIM could model cropping system outcomes similar to results observed in the field during the years 2008-2010. The time-series model used the full length of weather records from Zombwe (66 years) and Kasungu (83 years), and was run without reset for a continuous series of ten-year time periods.

2.3. Calibration model

The calibration model was run for the years 2008-2010 using data from Zombwe and included simulations of continuous maize controls at 24 and 92 kg N ha^{-1} in 2009 and 2010 as in the field trials. The pigeonpea-maize rotation system with 24 kg N ha^{-1} applied in maize years only was simulated, with pigeonpea planted in 2008 and 2010, and maize in 2009. The maize-pigeonpea intercrop with 24 kg N ha^{-1} was simulated for the 2008 and 2010 seasons, as field data was only available for those years. Simulations used maize cultivar MH 17, already

parameterized in APSIM, at a plant density of 3.7 plants m^{-2}. The built-in long-duration pigeonpea cultivar showed satisfactory performance, and given the lack of available calibration data it was used without modification. This was planted at lower density (2.2 plants m^{-2}) to account for high early plant mortality and damage in field experiments.

Soil nitrogen, organic carbon, surface residues and water content were initialized on July 15, every year in the case of the continuous maize systems to simulate true field conditions and eliminate carryover errors. The rotation system was reset after maize harvest and prior to pigeonpea planting, in order to accurately model maize yield response to pigeonpea in the previous year. Intercrop simulations were run independently for the two years, since pigeonpea was still in the field at the reset date. Surface organic matter was set to 300 kg ha^{-1} maize residues, consistent with farmer practice (Chikowo et al., 2008). Initial inorganic nitrogen was set to 4.25 kg N ha^{-1}, slightly below the average of measured values from the field sites which had been previously planted to unfertilized maize. This value was adjusted to better match yields in continuous maize systems and to prevent large jumps in inorganic nitrogen at reset.

2.4. Time series model

Once the model was properly parameterized and evaluated, a second set of simulations were run for both Kasungu and Zombwe, for the entire duration of each weather data set: 66 years for Zombwe and 83 years for Kasungu. The time series model only included three field treatments: continuous maize with 24 kgN ha^{-1}, a maize-pigeonpea intercrop with 24 kgN ha^{-1}, and a maize pigeonpea rotation with 24kgN/ha applied in maize years, simulated for both maize and pigeonpea entry points to provide maize and pigeonpea yield data in each year. These were run over ten year time series and not reset each year, which allowed novel insights into the medium to long-term impacts of using a diversified system. Simulations were replicated ten

times, with start dates in sequential years such that each year from system establishment was represented in each calendar year (Fig. 1). Residue management was performed separately for each crop: 80% of maize residues were removed to avoid early-season immobilization of N which substantially reduced yields, while pigeonpea residues were incorporated. The same soil profiles were used for both sites, which are consistent with soil properties measured on smallholder fields in the Kasungu area (Phiri et al 2010), though soils there tend to be most similar to the lower fertility, sandier type (Soil LF).

2.5. Calculation of yield and N effects

APSIM calculates a daily value of nitrogen and water stress for plant processes including photosynthesis, biomass expansion, and grain fill. These values ranged from zero (no stress) to one. Summing these values over the growing season provided a measure of total nitrogen or water stress of the crop. For this analysis we used N or water stress for photosynthesis, since photosynthesis occurs throughout the growth period. In some cases we isolated the yield and nitrogen stress effects of maize-legume systems as compared to continuous maize. In these cases, yield increase was calculated as a percentage of continuous maize yield by the formula:

(1) Yield Effect =(Yield of maize-legume system — Yield of continuous maize)/(Yield of continuous maize).

Reduction in N stress was calculated similarly, using model-calculated cumulative N stress for photosynthesis over the growing season and the formula:

(2) N Effect = (N stress in continuous maize —N stress in maize-legume system)/ (N stress in continuous maize).

When either yield or stress was zero in continuous maize, values were excluded.

2.6. Analysis of model results

Analysis was conducted using the statistical software R (R Development Core Team, 2011). Models were fitted using the built-in linear modeling function lm(), which calculates standard model diagnostics for linear fixed-effects models. Because the objective of the data analysis here is largely exploratory, we focus on trends in model results that illustrate underlying mechanisms. To simplify analysis, time since reset, representing time since establishment of the system, was grouped into early (years 2-4), mid (years 5-7) and late (years 8-10) periods. Analysis excluded the first (establishment) year, as rotation effects were not expected until after one year of pigeonpea growth.

3. Results

3.1. Calibration of model performance

Results in the evaluation model were generally within one standard deviation of measured maize yields and biomass. In most treatments modeled yields were above the experimental mean yield (Fig. 2). This slight over-prediction of on-farm yields is to be expected, since we could not account for pest and disease pressure, which may have significant impacts on-farm. We are also not accounting for the effects of phosphorous deficiency, which was observed on several farms in field trials (Mhango et al., 2012), because phosphorous sensitivity in

APSIM's pigeonpea module is not fully developed. Most important for our purposes, relative yields among systems are accurately represented.

Pigeonpea yield and biomass were also overestimated by the model. Early leaf senescence, combined with high levels of pest pressure, likely contributed to lower field-measured yield and biomass than simulated values. Mean field-measured pigeonpea yields in 2008 and 2009 ranged from 119 to 266 kg ha^{-1}, with a maximum reported yield of 953 kg ha^{-1} in the rotation system in 2009. Mean field-measured biomass ranged from 806 to 3307 kg ha^{-1}, with a maximum of 7040 kg ha^{-1}, again in the rotation system in 2009 (Mhango, *unpublished data*). Modeled yields ranged from 263 to 698 kg ha^{-1}, and biomass ranged from 3016 to 6981 kg ha^{-1}, which are consistent with results reported for Malawi and Tanzania (Myaka et al., 2006).

3.2. Systems including pigeonpea show higher yields than continuous maize systems.

Results from the time series model showed that rotation systems outperformed continuous maize on all soil types at both Kasungu and Zombwe (Fig. 3). The intercrop resulted in lower maize yields than those in continuous maize only for the most fertile soil type (Soil HF) during the early period in Zombwe. For the same soil type and period at Kasungu the intercrop produced similar yields to continuous maize. In all other periods, and for the other soil types, maize yields in the intercrop were greater than those in continuous maize. All systems showed improved productivity over the course of the 10 years between resets, with most increases within the first five years. Continuous maize yields increased only slightly over time, because soil conditions in year one represented soil status following unfertilized continuous maize. Repeated fertilizer inputs and small additions of organic matter resulted in minimal improvements in yields over time. Yield increases between periods were greatest in intercropping systems, while rotation

systems provided the highest yield overall in maize years. The greatest differences between continuous maize and maize-legume systems were observed in the least fertile soil (Soil LF).

At Zombwe, maize yield in intercrop systems was positively correlated with the previous year's pigeonpea biomass throughout the 10-year period from establishment ($p < 0.05$). Rotation systems show a more complex relationship, with interactions between soil type and establishment period. Early in the 10-year cycle (2-4 years from establishment), effects were positive and significant (at $p < 0.05$) for Soil HF, but insignificant for the other two soils. In later years, there was no significant effect in Soil HF but soils MF and LF showed small negative trends. At Kasungu the effect of previous year pigeonpea biomass was minimal, and all R^2 values were less than 0.1.

3.3. Risk and yield distribution change with cropping system and over time

Yield distributions were wider for maize-legume systems than for continuous maize, and wider for intercrops than for rotations (Fig. 4). In higher fertility soils during early establishment, legume systems showed increased risk for low yields. At Kasungu, the risk of yield below 1000 kg ha^{-1} ranged from 13%-16% in the intercrop system, with the highest risk in the low fertility soil. Risk of low yield in rotation was similar to or lower than risk in continuous maize, with values ranging from 7%-12%. As time from establishment increased, risk of low yield in the intercrop system is reduced to levels near that of continuous maize. Risk in the rotation system also declined slightly. Yield variability and risk of low yields were higher at Kasungu than at Zombwe in all cases. Yield effects of legumes on maize were substantial, providing up to a 150% increase over continuous maize yields. This effect was greatest in Soil LF, the sandy, low fertility soil.

Examining yields for individual years showed that maize yield following pigeonpea was very rarely lower than maize yield following maize. Continuous maize out-yielded maize following pigeonpea in only 3.1% of years at Zombwe, and 6.7% at Kasungu. Intercrops were riskier, particularly in the period of early establishment, where maize yield in intercrop was lower than maize only yield in 10-30% of years at both sites. This risk was reduced dramatically with time, so that in the 3-5 year period, only 4% of years show reduced yields in intercrops.

3.4. Nitrogen effects of legumes

In all systems, modeled yield is limited by nitrogen availability, as expected for low-level fertilizer applications in relatively low-fertility soils. The nitrogen effects on maize due to the inclusion of pigeonpea were isolated at Zombwe using the yield and nitrogen effects calculations described in Equations 1 and 2 (Fig. 5). A linear model including treatment (intercrop or rotation) and soil type as fixed factors and N effect as a covariate was fitted to yield effect data at Zombwe. The model had an overall R^2 value of 0.78. Including period from establishment improved the model only slightly, to an R^2 value of 0.79, so we used the more basic model for simplicity. Based on the linear model, we fitted separate regression lines for each soil type-treatment combination. The slope of the regression was highest in the low fertility soil and the R^2 value decreased in the lower-fertility soils (Fig. 5).

The effect of N stress reduction in Kasungu is less pronounced. A similar model of yield and N stress effects produced many non-significant slopes, and R^2 values of less than 0.2 in all cases. It is clear that while in some cases nitrogen is limiting yields in Kasungu, other factors may also be important determinants of maize yield at this site.

Both intercrop and rotation systems increased organic carbon content in soils, particularly in the upper 15 cm. At Zombwe, the organic carbon content for soil HF in the upper 15 cm

increased from 0.78% to 0.89% in the intercrop system and 0.86% in the rotation. Organic carbon for soils MF and LF increased from 0.58% to 0.66% in rotation for both soils, and to 0.70% and 0.71% in intercrop for soils MF and LF, respectively. Soil carbon in the continuous maize system remained approximately constant in all soils. Results were similar at Kasungu.

3.5 Water stress effects and impacts on yield

Crop water stress was important for reducing the beneficial effect of legumes at Kasungu. In Zombwe there were so few instances of high soil water stress, we were not able to draw conclusions. However, drier conditions and a longer record at Kasungu provided enough instances of substantial water stress to allow meaningful analysis. There is a clear influence of rainfall at Kasungu, and similar to values reported for Zimbabwe (Shamudzarira and Robertson, 2002), this effect was most pronounced at rainfall amounts below 550 mm (Fig. 6). At low rainfall levels, the beneficial effects of legumes were reduced. Isolating the legume effect using Equation 1 showed an increase in the beneficial effect of both rotation and intercrop with increased rainfall (Fig. 7). Separating results by soil type and treatment, a quadratic regression was fitted to yield effect data after discarding outliers (yield effect > 350). All regressions are significant at $p < 0.05$. At Kasungu in the rotation system, the effect of legume diversification is negative when seasonal rainfall was below 270 mm in the low fertility, sandy soil and 300 mm in the higher fertility, finer-textured soil. The intercrop system showed greater variability, and the trend showed negative effects up to rainfall levels of 317 mm and 390 mm in LF and HF soils, respectively. Results in Zombwe were similar, though trends were less clear at this higher-rainfall site.

In cases where cumulative soil water stress was greater than one, there was a clear relationship between soil water stress and yield. In-crop rainfall amounts in stressed years ranged

up to 743 mm (above the mean value over all years at Kasungu of 739 mm), with a mean value of 478 mm. Both intercrop and rotation treatments were more likely to experience yield-impacting levels of water stress than continuous maize. When cumulative soil water stress was higher than 10, modeled yields were reduced by 10-15% (Fig. 8). Soil water stress levels increased with time from establishment as nitrogen stress declined and yield increased, which caused plants to use more water (Fig. ?).

The effect of water stress is most pronounced at critical times in crop development. Using model-identified crop stages, soil moisture content was examined early in the growing season (from emergence through flag leaf stage) and near flowering (floral initiation and flowering stages) (Fig. 9). Soil water status was influenced by both soil and treatment, with soil HF having generally higher extractable soil water. Maize-legume systems had lower soil moisture content than continuous maize systems, especially early in the season. Soil water at flowering was much closer among systems, as soil water recharge occured with early season rainfall (Fig. 9).

In Zombwe, overall rainfall amount was not well correlated with maize yields even in years with rainfall below 550 mm (data not shown). Relationships between yield and soil water at critical crop stages were also unclear. Yields were, however, negatively correlated with the number of dry spells of 10 days or longer during the growing season, for all rainfall amounts in both rotation and intercrop systems. In contrast, continuous maize yields showed no correlation with dry spells. This effect was not observed at Kasungu.

Pigeonpea, as a long-duration crop, was more adversely affected than maize by low rainfall and shortened rainy seasons, in both Zombwe and Kasungu. The effect of dry spells observed at Zombwe for maize yields was not seen for pigeonpea.

4. Discussion

4.1. Model performance

APSIM was able to realistically simulate both rotation and intercrop systems, producing maize and pigeonpea yields similar to those observed in participatory field trials in Northern Malawi and reported elsewhere (e.g., Myaka et al. 2006, Høgh-Jensen et al. 2007, Mwale et al. 2011). While the field data used in this study do not provide calibration of long-term effects, other work has confirmed the ability of APSIM's components to simulate long-term soil processes (Probert et al., 1998). We have found that with limited additional soil sampling and processing, the data collected from participatory trials was sufficient to adequately parameterize APSIM. Further adjustments to the model are possible and could potentially increase precision. For example, we used a generic long-duration pigeonpea cultivar because of the lack of available data to further calibrate this model. With additional data we would be able to adjust parameters related to crop duration as well as nitrogen fixation. APSIM's Pigeonpea module, like other legume models, assumes the plant will preferentially use soil nitrogen sources including inorganic N from applied fertilizer before utilizing biologically fixed nitrogen. This may not be accurate as it has been found that pigeonpea may fix up to 85% of the nitrogen it uses (Tobita et al., 1994). However, overall our model performed adequately so we considered it appropriate to use our model results to address our research questions.

4.2. Maize-legume systems increase maize yield over time

While maize-legume systems had higher variability in nearly all years, the impact associated with inclusion of pigeonpea was positive. Overall, both intercrop and rotation systems outperformed the continuous maize control treatment (Fig. 3), and the magnitude of the effect increased with increasing time from establishment. Our results agree with field studies in Malawi which showed benefits of pigeonpea and other long-duration legume systems for increasing

productivity of maize (Kamanga et al., 2009, Snapp et al., 2010). The long-term consequences of continuing maize-legume systems over several years has generally been difficult for farmers to consider, given high discount rates applied to future yields (Waddington and Karigwindi, 2001). Long-term impacts on soil carbon are difficult to measure in on-farm trials, due to variability which may disguise any changes over short-term time frames (Kravchenko and Robertson, 2011). Despite the potential simulation models have for understanding soil processes, most modeling studies have not investigated the long-term impacts of a given cropping system, likely due to the possibility for compounding errors in nitrogen, carbon and water from year to year. Further modeling efforts, especially when combined with long-term field experiments, would provide valuable additional information for both farmers and researchers.

There were clear differences in maize yield response to legumes due to differences in soil type. The greatest yield benefit was seen in low fertility, sandy soils, where small increases in available nitrogen, soil cover and organic carbon were most beneficial. Yields under maize-legume systems at Zombwe after 10 years were the same across all three soil types (Fig. 3), despite continued differences in continuous maize yields. At Kasungu differences by soil type persisted, particularly between soils HF and LF, which were most likely caused by higher soil water stress in the sandier soil at Kasungu.

4.3. Risk of crop failure remains low in maize-legume systems

We found that pigeonpea in rotation was relatively low-risk, particularly in Zombwe where moisture constraints are lowest (Fig. 4). It was rare for modeled maize yields in maize-pigeonpea rotation systems to be lower than those of continuous maize systems in the same year. Additionally, the overall risk of low yield was generally equivalent to, or lower than risk in continuous maize systems. Intercrops appeared to be more risky than rotation systems,

particularly in early establishment years. Risk in all systems was slightly increased in Kasungu, due to increased water stress, and risk remained elevated over time. Over a two-year cycle, intercrops produced higher quantities of maize grain on average than rotation systems, but also had slightly higher risk. This system may be more attractive to farmers, depending on their risk tolerance, value placed on the legume crop, and the amount of land available to satisfy maize food requirements.

4.4. Soil water and nitrogen trade-offs are seen in low-rainfall conditions

It is clear that a trade-off exists between increased available nitrogen and higher soil water stress in legume systems. However, in both sites, the effects of increased nitrogen greatly outweighed increases in soil water stress. At Zombwe the nitrogen effect was clearly the dominant predictor of yield in the model (Fig. 5). When yields occurring in water-stressed years were removed at Kasungu, N stress became similarly dominant. As the model could not account for other potential benefits of diversification such as pest control or increased micronutrient availability (Wani et al., 1995), the dominant influence of nitrogen stress was not surprising. Increased water use in the intercrop and rotation system led to decreased yield only when precipitation during the growing season was below approximately 300 mm, which was a rare condition, especially at the Zombwe site. Nitrogen and soil water stress combined to explain nearly all of the variation in modeled yield, particularly in the rotation system. There was a larger amount of remaining variability in the intercrop, indicating the potential importance of other factors, such as competition for light between maize and pigeonpea.

5. Conclusions

The approach used here to integrate modeling with participatory research shows promise for scaling up results from smaller scale field research and for generating new insights. Our

results show that maize-pigeonpea cropping systems are viable, low-risk options for improving crop production and soil fertility with minimal reliance on external inputs. Application of the APSIM model over a decade indicated that there was some initial risk of depressed maize yield associated initially with soil moisture depletion for intercrop systems. However, the risk of reduced maize yield appeared to be mitigated over time. This novel application of a crop simulation model over multiple years in a smallholder context highlighted trade-offs between increased nitrogen availability and decreased soil moisture. We were also able to elucidate the time frame during which these systems have a higher risk for failure, which may pose a barrier to adoption by local farmers. Interestingly, we found that intercrops only posed a risk to cereal production when rainfall was below 300mm. Overall, our findings show that pigeonpea has value as a soil productivity enhancing intervention, particularly when targeted to low fertility soils.

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Figure captions

Fig. 1. Schematic depiction of time series model setup. Simulations are run continuously for ten years, after which soil parameters are reset. Model is run ten times (only three runs are shown here) with staggered start dates to maintain a high level of replication.

Fig. 2. Comparison of field-measured data and results from the simulation model used for evaluation. Means (± 1 SD) reported for maize biomass and grain yield from 2009-2010 field experimentation at Ekwendeni, Malawi. Where columns are missing, field data was not available. Points represent model results from simulations run on three soil types: HF=high fertility, MF=medium fertility, LF=low fertility. Treatments are described in methods.

Fig. 3. Mean maize yields for 10 years from system establishment for three cropping systems in three soil types. Time series model results averaged over 83 years at Kasungu and 66 years at

Zombwe, northern Malawi. Error bars are + 1 SE of the mean over the same time period. Variation is based on differences in weather from year to year. Soil types defined in methods. HF=high fertility, MF=medium fertility, LF=low fertility.

Fig. 4. Cumulative probability distributions of maize yields for three cropping systems in three soil types. Time series model results from simulations of 83 years at Kasungu and 66 years at Zombwe, northern Malawi. Results plotted separately for each soil type and period from establishment. Periods "early" and "mid" refer to 2-4 and 5-7 years from system establishment, respectively. Results for the "late" period are not shown but were similar to period "mid". Soil types defined in methods. HF=high fertility, MF=medium fertility, LF=low fertility.

Fig. 5. Effect of legume diversification on maize yields and cumulative nitrogen stress relative to continuous maize at the same fertility level. Continuous maize yield is zero. Negative N stress reduction (x-axis) values correspond to increases in nitrogen stress. Time series model results from simulations over 66 years at Zombwe, northern Malawi. Points displayed are a random sample of the full data set. Regression lines are significant at $p < 0.05$ and shaded region represents standard error of the regression. R^2 values for regression lines range from 0.65 to 0.87. Soil types defined in methods. HF=high fertility, LF=low fertility.

Fig. 6. Maize yield and in-crop rainfall for three maize-pigeonpea cropping systems. Time series model results are from simulations of 83 years at Kasungu, northern Malawi. Results were restricted to in-crop rainfall below 550 mm. Lines represent linear regression and are significant at $p < 0.05$. Intercrop R^2=0.76, Rotation R^2=0.84, Continuous maize R^2=0.69.

Fig. 7. Effect of legume diversification on maize yield relative to continuous maize at the same fertility level, as influenced by in-crop rainfall. Continuous maize yield is zero. Negative N stress reduction (x-axis) values correspond to increases in nitrogen stress. See Results for further information. Time series model results from simulations of 83 years at Kasungu, northern Malawi. Points plotted are a random sample of the full data set. Regression lines are significant at $p < 0.05$ and shaded region represents standard error of the regression. R^2 values range from 0.33 to 0.58. Soil types defined in methods. HF=high fertility, MF=medium fertility, LF=low fertility.

Fig. 8. Percentage of years with high levels of soil water stress (stress levels corresponding to 10-15% yield reduction) for three cropping systems in three soil types. Time series model results averaged over 83 years in Kasungu, northern Malawi. Periods "early" and "late" refer to 2-4 and 8-10 years from system establishment, respectively. Soil types defined in methods. HF=high fertility, MF=medium fertility, LF=low fertility.

Fig. 9. Mean (± 1 SE) extractable soil water at (a) early season and (b) flowering plant growth stages for three cropping systems in three soil types. Time series model results from simulations of 83 years in Kasungu, northern Malawi. Error bars are standard errors of the mean. Soil types defined in methods. HF=high fertility, MF=medium fertility, LF=low fertility.

Table captions

Table 1. Soil properties used to parameterize APSIM simulations.